Life prediction of a steam piping by Small Punch and uniaxial creep testing

Rantala, Juhani

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Life prediction of a steam piping by Small Punch and uni-axial creep testing

Rantala JH

VTT Technical Research Centre of Finland Ltd
Espoo, Finland

Abstract

A series of Small Punch creep tests were performed for a 10CrMo910 steam piping from a chemical plant and the results were compared against uniaxial creep test results. The Small Punch (SP) test durations were relatively short compared to the durations of the uniaxial test series. The durations of the longest SP test was only only five times longer than the shortest SP test, while in the uniaxial test series the factor was 40. The analysis suggests that the spread in the SP test durations should be of the same magnitude in order to give a firm basis for life assessment.

The SP test equipment was designed to provide oxygen free conditions in order to avoid oxidation of the specimens, and this would help in performing longer tests. Oxygen content well below 10 ppm was measured from the exhaust gas.

1. Introduction

A uniaxial creep test series was performed for a 10CrMo910 (P22) steam piping from Neste oil refinery in Porvoo for life assessment in 2010 and in 2017 a Small Punch creep test series was performed for samples machined from the bars cut off during the manufacturing of the uniaxial samples. The purpose of the Small Punch test series was to find out whether miniature testing can be used for life prediction instead of the traditional uniaxial creep testing which inevitably requires cutting a section of the piping and welding a new piece instead. Small Punch testing for material samples removed by surface sampling would reduce the associated sampling cost remarkably.

EN standard for Small Punch tensile and creep testing [1] is being prepared, based on the old CEN Workshop Agreement [2], and in this paper the analysis methods [3] in the draft standard are applied on the SP results of this study.

2. Materials and methods

The dimensions of the 10CrMo910 100 bar line are 193.7 x 22.2 mm, internal operating pressure 100 bar, design pressure 116 bar, operating temperature 520°C, design pressure 535°C, internal medium steam. At the time of sampling in 2010 the piping had been in operation for 201500 hours. The samples used in this paper have been extracted from a pipe section which showed some bending in the visual inspection. Uniaxial tests had been carried out in 2010 for the base material. The SP specimens (ϕ8.0*0.5 mm) had been manufactured by Materialovy a Metallugicky Vyzkum s.r.o. in Ostrava, Czech Republic from the bars cut off during the manufacturing of the uniaxial samples.

In a SP tensile test a constant displacement rate of (typically) 0.3 mm/min is applied, while in a SP creep test constant load is used. In high temperature tensile and creep testing the test specimen has to be protected from oxidation and therefore a gas tight test rig had been developed at VTT where argon 6.0 protective gas is used to remove oxygen. To allow frictionless movement and gas tightness a special metallic bellow is used as shown in Figure 3, where the test device is shown without the thermal insulation.

The puncher displacement is measured by a transducer shown in Figure 3 and the deflection of the specimen is measured from below by a special thermocouple & ceramic extensometer combination. In this way the specimen temperature is measured directly from the specimen. Additional thermocouples are installed elsewhere in the rig in order to monitor the temperature gradients. Heating is provided by two resistance heating coils wound around the tools.

Figure 1. Small Punch creep rig at VTT with thermal insulation removed. Parts from above: load cell, displacement transducers, loading bar, metallic bellow and the rig with two heating cables clamped in place by stainless steel sheets.

3. Uniaxial and Small Punch creep test results

Four traditional uniaxial creep tests had been carried out in 2010. The results are shown in Table 1. In the table are given also the minimum strain rate and the Monkman-Grant (MG) constant, which is the product of rupture time and the minimum strain rate. The Small Punch creep test results are shown in Table 2 where umin is the deflection u at minimum displacement rate. The umin values for the tests SPC002 and 004 have been corrected for an unintended movement of the specimen holder at the start of the tests. All tests were planned to be conducted at a stress of 66 MPa calculated by the old Code of Practice [2], but due to a systematic error in the load calculation the actual test stress was 57.4 MPa. The systematic error in the load calculation resulted in a load which was wrong by a factor of $2^{-1/5}$, so when the rupture times and the minimum strain rates are corrected by assuming a stress exponent of 5, the correction factor becomes exactly 2. The minimum strain rates are multiplied by this factor and the rupture times are divided. The corrected results are shown in Table 3.

In other SP tests it was discovered that in some cases the specimen holder had moved upwards by 0.6 mm during the setting up of the test. This unintentional movement had obviously happened in tests SPC002 and 004. The corrected puncher displacement curves are shown in Figure 2. The test SPC001 was interrupted due to breaking of one of the heating coils. Fortunately, the test had already passed the minimum displacement rate as shown in Figure 6.

Table 1. Uniaxial creep test results of the 100 bar line at 66 MPa.

	Stress	Temp	tr	min. strain	
Test number	[MPa]	[°C]	[h]	rate 1/h	MG
y334 BM2	66	676	48	1.13E-03	5.42E-02
y332 BM1	66	644	311.5	1.57E-04	4.89E-02
y336 BM3	66	623.5	1241.5	4.16E-05	5.16E-02
y338 BM4	66	615	1891.3	2.68E-05	5.07E-02
				MG average	5.14E-02

Table 2. Small Punch creep test results at 57.4 MPa.

				Min displ	Min strain	
Test	Load [N]	Temp T1	umin [mm]	rate [mm/h]	rate [1/h]	tr [h]
SPC001	107.72	646	0.503	8.51E-04	1.28E-04	interr.
SPC002	107.7	646.7	0.533	1.50E-03	2.25E-04	578.7
SPC003	107.7	663.3	0.494	2.72E-03	4.08E-04	269.1
SPC004	108.63	667.8	0.608	7.13E-03	1.07E-03	110.6

Table 3. Small Punch creep test results corrected to 66 MPa.

			Min displ	Min strain	
Test	Temp T1	umin [mm]	rate [mm/h]	rate [1/h]	tr [h]
SPC001	646	0.503	1.70E-03	2.55E-04	interr.
SPC002	646.7	0.533	3.00E-03	4.50E-04	289.3
SPC003	663.3	0.494	5.44E-03	8.16E-04	134.6
SPC004	667.8	0.608	1.43E-02	2.14E-03	55.3

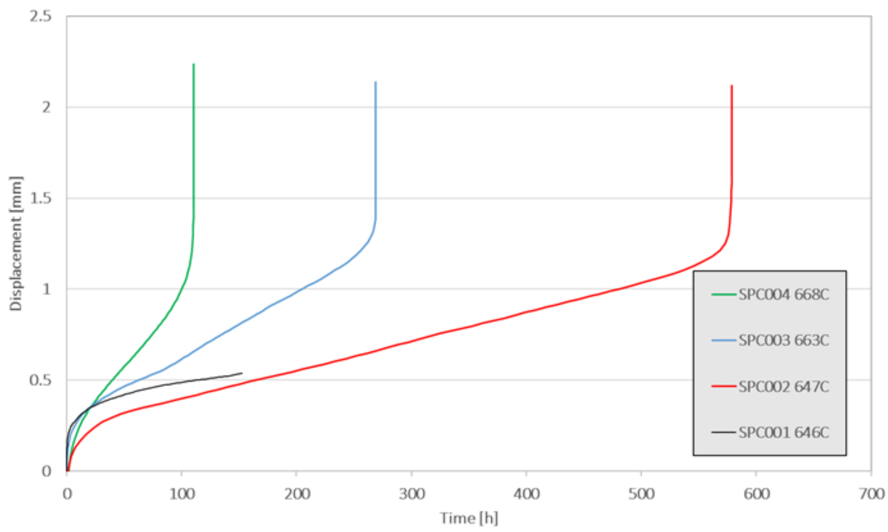

Figure 2. Puncher displacement curves of the Small Punch tests.

The displacement curves of the four SP creep tests are shown in Figure 2. As in this test series the specimen deflection measurement was not yet used in all of the tests, only the puncher displacement is used in the analysis. The displacement rate curves are shown in Figure 3. Note that for the test SPC003 the minimum strain rate curve is rather flat, which makes it a little ambiquous to determine the time value of the minimum rate, but the absolute minimum is used. The original and the corrected creep rupture times are shown in Figure 4.

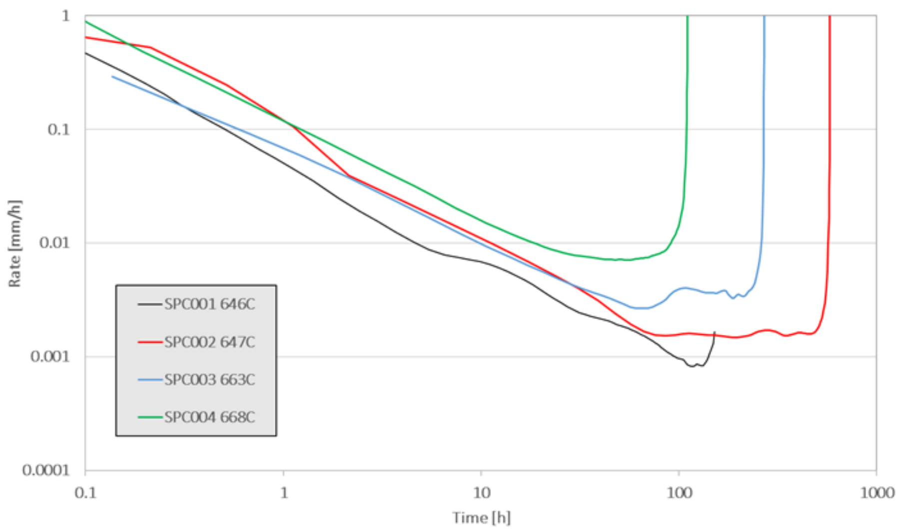

Figure 3. Displacement rate curves of the SP creep tests at 57.4 MPa.

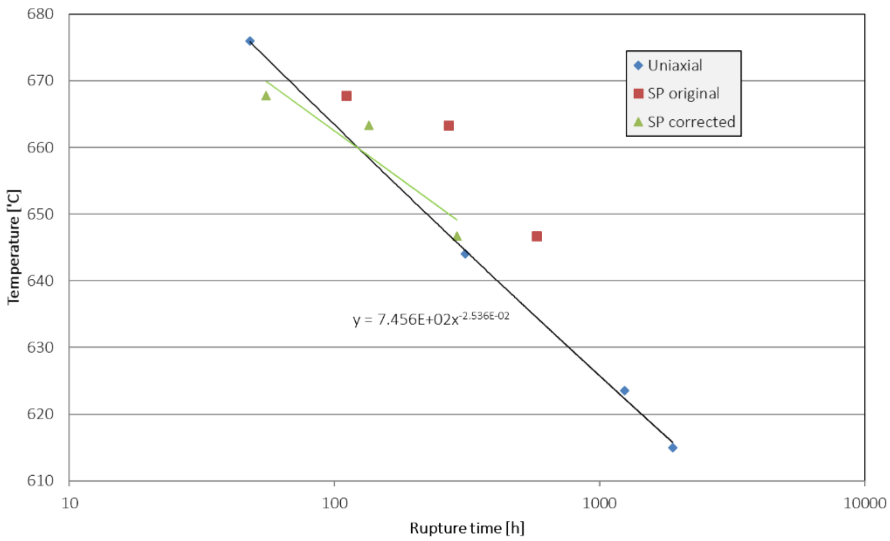

Figure 4. Uniaxial and SP creep test results of the 100 bar line.

The correlation of the corrected SP creep rupture times (the green data points) and the uniaxial results in Figure 4 is very good. Also the deviation between the uniaxial and SP minimum creep rates in Figure 5 are very reasonable although there is a systematic difference in the slope between the uniaxial and SP results.

All available data from a P92 pipe, a P92 forging and a 316L plate from the organisations involved in the Small Punch standardisation activity was gathered and analysed in order to improve the data analysis methods. The results have been published in [3]. The Equation (8) in [3] was applied to the data of this report and the results are shown in Figure 5. This equation gives an estimate of the minimum uniaxial strain rate (in mm/h) based on the minimum displacement rate (in 1/h) measured in the Small Punch creep test:

$$\dot{\varepsilon}_{min} = 0.3922\dot{u}_{min}^{1.1907} \qquad \text{(Eq.1)}$$

Because in this test series only the puncher displacement is used, it is assumed that the displacement rate can be used instead of the specimen deflection rate. The data points in brown in Figure 5 and in Table 2 and Table 3 are based on a linear relationship between the two aforementioned rates so that:

$$\dot{\varepsilon}_{min} = 0.15\dot{u}_{min} \qquad \text{(Eq. 2)}$$

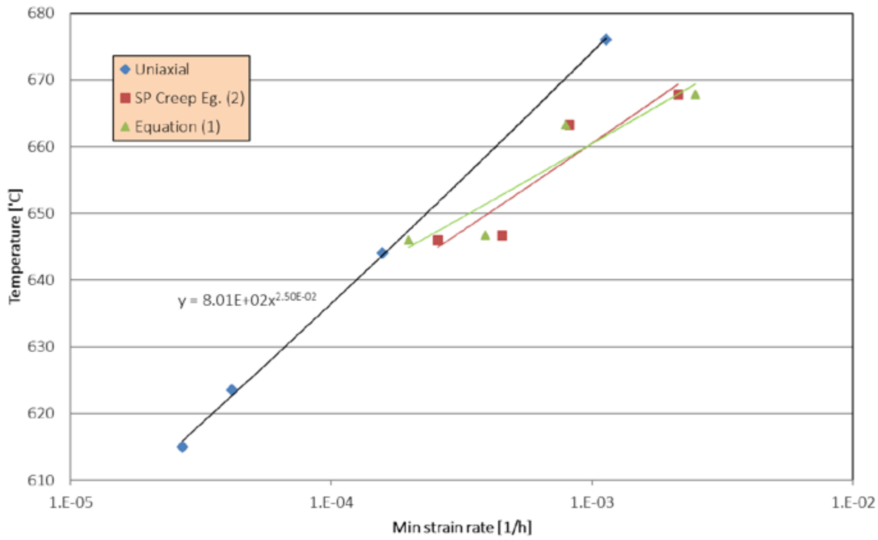

Figure 5. Measured minimum strain rates of the SP creep test series.

The reference [3] reports also on an attempt to improve the accuracy of the stress to SP load conversion based on the idea that the perimeter where the effective stress is active becomes larger when the puncher penetrates the deeper into the specimen. The empirical "force to stress conversion" method based on large data set of low alloy and 9Cr steels is given as a function of u_{min} (the deflection at minimum deflection rate):

$$F/_{\sigma} = 1.9162 \cdot u_{min}^{0.6579} \; [N/_{MPa}] \qquad \text{(Eq. 3)}$$

Another model is based on the modified Chakrabarty model and is also expressed in terms of the deflection at the minimum deflection rate:

$$F/_{\sigma} = 0.6143 + 1.2954 \cdot u_{min} \; [N/_{MPa}] \qquad \text{(Eq. 4)}$$

When these are applied to the data shown in Table 2 we can see in Table 4 that although the idea behind the equations above is correct the calculated stresses are much bigger than the stress 57.4 MPa calculated according to the old Code of Practice [2].

Table 4. Uniaxial stress equivalents calculated by Equations 3 and 4.

Test	Load [N]	umin [mm]	PsiEFS	Calc. Stress	PsiMCH	Calc. Stress
SPC001	107.72	0.503	1.219	88.3	1.266	85.1
SPC002	107.7	0.533	1.266	85.1	1.304	82.6
SPC003	107.7	0.494	1.205	89.4	1.254	85.9
SPC004	108.63	0.608	1.382	78.6	1.402	77.5

4. Life prediction

When looking at Figure 4 it is obvious that the uniaxial test series offers a much better basis for life assessment than the SP test series, mainly for two reasons: 1) the uniaxial test series shows almost exceptionally little scatter in rupture time as the data points fall almost perfectly on the trendline and 2) the spread of uniaxial rupture times is much larger than for the SP test series. The SP test durations could in principle be extended to cover the same range of times as in uniaxial testing, but SP testing is more expensive than traditional creep testing and in practice most laboratories don't have tens of SP rigs waiting for contract work. In terms of scatter the SP testing will suffer from scatter because of the small specimen thickness of 0.5 mm which is in many cases just 10 times the grain size, which makes the SP test more sensitive to local material imperfections and thus scatter. It can be seen in Figure 4 that although the SP data points agree rather nicely with the uniaxial data, the trendline based on just three SP data points differs a lot of the uniaxial slope. It the life assessment would be based on just the SP results from so few data points at a narrow temperature range, the life assessment would inevitable become large unconservative as shown in Figure 6. The accuracy would improve if more SP tests could be performed at lower temperatures.

However, in many cases the plant operators need to prioritise pipings to be inspected or replaced and when SP tests from different piping are compared, the SP testing is accurate enough to show which piping has suffered most during service than the others and then the plant owner can plan the maintenance work or investments based on valid experimental evidence.

SP test results can also be used for life prediction by using Monkman-Grant (MG) type of relationships between the measured SP minimum creep rates and uniaxial rupture times. An attempt into this direction is shown in Figure 7 where three different correlations are used. Equation 10 refers to the equation in reference [3] where the rupture time t is expressed as a function of the minimum SP deflection rate:

$$t = 0.521 \cdot \dot{u}^{-0.959} \qquad \text{(Eq. 4)}$$

The “MG prediction” refers to a straight forward MG relationship where the MG average value of $5.14 \cdot 10^{-2}$ is divided by the minimum strain rate calculated by Equation (2) of this paper. “Equation 5” refers to equation 5 in [3] with the constant values given for P92 as a function of the calculated minimum SP strain rate:

$$t = 0.0443 \cdot \dot{\varepsilon}^{-0.9443} \qquad \text{(Eq. 5)}$$

It can be seen in Figure 7 that the slopes of the MG predictions are parallel to the SP slope, but they differ quite a lot in terms of rupture time and could not be used for life assessment as such. It is expected that the SP standard [1] will improve in this respect before it is published.

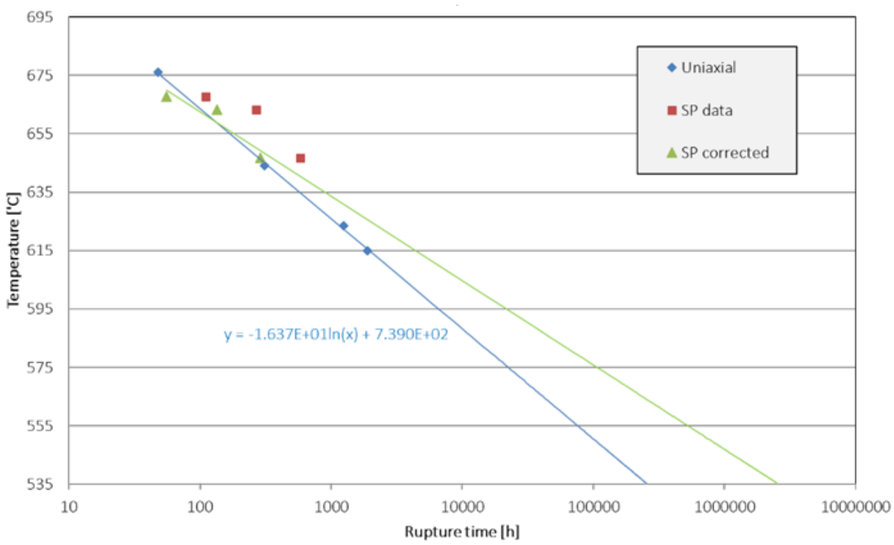

Figure 6. Life prediction based on uniaxial and SP test results at 66MPa.

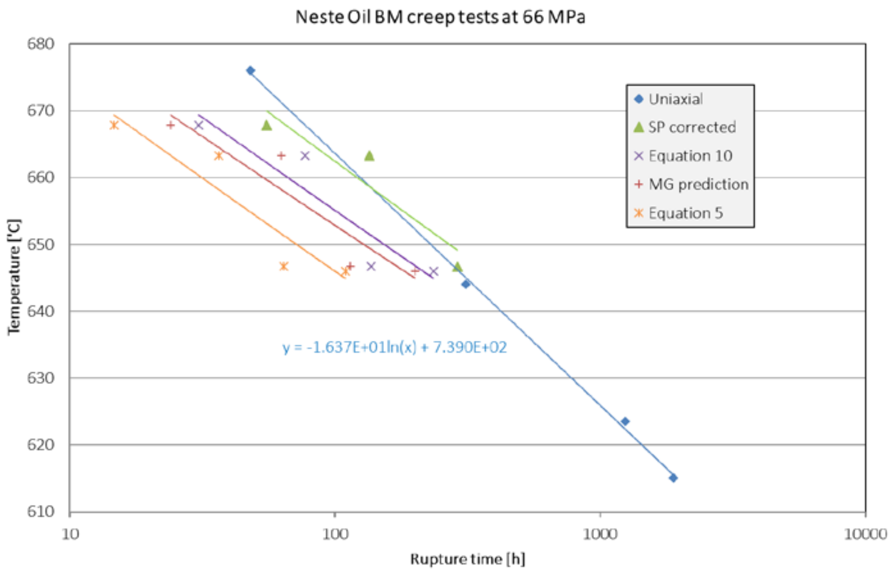

Figure 7. Monkman-Grant predictions of SP rupture times.

Acknowledgements

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